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THE MOST LUMINOUS RADIO GALAXIES

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RESUMEN

Se discuten las propiedades de las fuentes de radio extragalácticas más brillantes y de sus galaxias anfitrionas. Estas fuentes están asociadas con las galaxias más masivas conocidas hasta el corrimiento al rojo de al menos 2. Resultan ser una clase única de objetos para estudiar los núcleos galácticos extremadamente activos y sus galaxias anfitrionas, y representan retos para entender la formación de las galaxias más masivas.

ABSTRACT

The properties of the brightest extragalactic radio sources and their host galaxies are discussed. These sources are associated with the most massive galaxies known out to a redshift of at least 2. They provide a unique class of object for studying the most extreme active galactic nuclei and their host galaxies and present challenges for understanding the formation of the most massive galaxies.

Key Words: **COSMOLOGY — GALAXIES: FORMATION — RADIO CONTINUUM: GALAXIES**

1. INTRODUCTION

The brightest radio sources in the northern sky are contained in the Third Cambridge Catalogue of Radio Sources, the 3CR catalogue. In 1983, Robert Laing, Julia Riley and I produced a revised version of the catalogue, the 3CRR catalogue, with improved completeness (Laing *et al.* 1983). Virtually all the sources at $|b| \geq 10°$ are distant extragalactic objects. The 3CR sample is flux-density limited at $S \geq 10$ Jy at 178 MHz and so contains a mixture of nearby low radio luminosity objects and luminous distant objects. Since the sources were selected at a low radio frequency, virtually all of them are extended double radio sources.

There are significant differences between the radio structures of the extragalactic sources as a function of radio luminosity (Fanaroff & Riley 1974). In the Fanaroff-Riley Classes I objects (FRI), the maxima in the radio brightness distributions of the double radio lobes occur close to the centre of the radio structures, whereas in the Fanaroff-Riley Class II objects (FRII), the maxima are found towards the leading edges of the radio structures, what are often called edge-brightened radio sources. The correlation is in the sense that the most intrinsically luminous radio sources are all FRII sources and so, since the sample is flux density-limited, these are also the most distant sources in the sample – their redshifts z extend almost to $z = 2$. We will deal exclusively with the FRII sources in what follows. Almost all the radio quasars in the 3CR sample have FRII structures and amount to about 25% of the total number of FRII sources.

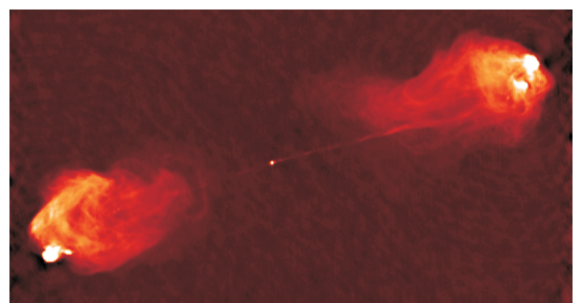

Fig. 1. The radio structure of the brightest extragalactic radio source in the northern sky, Cygnus A, a typical FRII radio source (Perley, Dreher and Cowan 1984).

The example of the typical FRII radio source, Cygnus A, is shown in Fig. 1. The radio emission is synchrotron radiation and the 'hot-spots' at the extremities of the radio lobes are powered by jets of relativistic material, the faint emission from which are visible in the radio image. Observations by the Chandra X-ray observatory have shown that the radio structure is enveloped in a hot X-ray halo associated with the bremsstrahlung of hot intergalactic gas surrounding the radio galaxy. The relativistic particles and magnetic fields in the lobes are more or less in pressure balance with the hot intergalactic gas, but the relativistic beams responsible for the radio emission bore their way out through the hot gas, leaving behind the wake of relativistic emitting material which is identified with the radio lobes.

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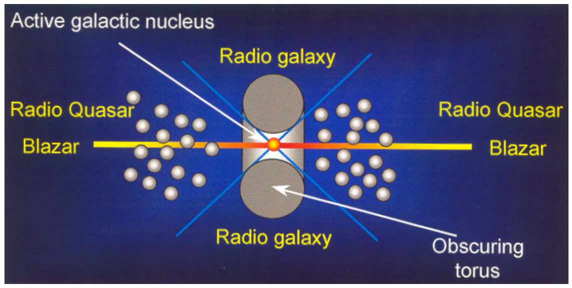

Fig. 2. Illustrating the orientation-based unification scheme for radio galaxies and radio quasars in the sample of FRII 3CR radio sources.

Because of the strong emission lines in their spectra, redshifts were available for complete samples of 3CR objects in the early 1980s, largely thanks to the efforts of Spinrad and his colleagues. It turned out that the redshift distribution for the FRII radio galaxies and radio quasars are the same and this could be explained by a orientation-based unification scheme in which the active nucleus is surrounded by an obscuring torus (Fig. 2). In fact, every test we have made of this scheme is in agreement with the simplest unification model – their cosmological evolution, the statistics of their numbers and sizes, their asymmetries, the presence of one/two sided jets and so on. This is an important result because it means that the host galaxies of the radio quasars are objects similar to the radio galaxies in the sample.

Both the radio galaxies and radio quasars display very strong evolution of their properties with redshift, or cosmic epoch. There is an enormous increase in the comoving space density of sources by a redshift of 2. Exactly the same form of strong evolution is found in optically selected samples of quasars. One of the objectives of our programme has been to understand the nature of these strong evolutionary changes which must be present in our sample of the brightest radio sources in the sky.

2. THE K-Z RELATION AND THE ALIGNMENT EFFECT

By the early 1980s, advances in infrared detector technology enabled even the most distant radio galaxies in our sample to be detected in the K (2.2 μm) infrared waveband. Simon Lilly and I discovered that the redshift K-magnitude relation for the radio galaxies was remarkably tight and could be extended out to redshifts of almost 2 (Lilly and Longair 1984). The radio galaxies at redshift 1–1.5 were about a magnitude brighter than would be expected according to the standard world models, but that was what would be expected if the stellar populations of the galaxies had evolved passively between redshifts $z \approx 1$ and the present epoch. Therefore, we had the possibility of finding out information both about the evolution of the stellar populations of these galaxies and about cosmological parameters. We started a new series of surveys to advance these studies when a major spanner was thrown in the works by the discovery of the alignment effect by McCarthy, Chambers and their colleagues (McCarthy *et al.* 1987, Chambers *et al.* 1987). They showed that the optical images of some of the radio galaxies were aligned with their radio structures and so all bets about the use of radio galaxies as cosmological probes were off.

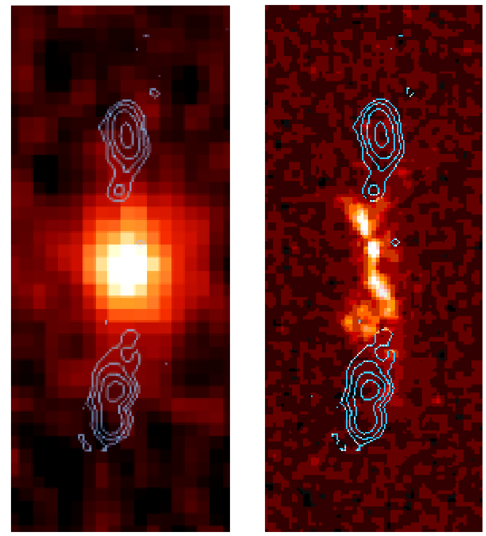

Fig. 3. (a) The infrared K image of 3C 266 with the contours of the double radio structure superimposed. (b) The HST optical image of 3C266 showing clearly the aligned optical emission (Best, Longair and Röttgering 1998).

Fortunately, as an interdisciplinary scientist for the Hubble Space telescope, I had guaranteed observing time to study the 3CR radio galaxies and so we put all the time into studying a complete sample in the redshift interval $0.6 \leq z \leq 1.8$, with a special emphasis upon understanding the alignment effect and the origin of the strong evolutionary effects present in the sample. We also secured excellent K-infrared images with the UK Infrared Telescope and high resolution radio maps with the VLA. An example of the alignment effect for the radio source 3C 266 is shown in Fig. 3.

This alignment effect was found almost exclusively in all the radio galaxies at redshifts $z \geq 1$. The strength of the alignment effect decreased with increasing linear size of the double radio structure indicating that the alignment effect is a temporary phenomenon stimulated by the passage of the radio jet (Best, Longair & Röttgering 1996). We began a major investigation of the nature of the optical emission and how it affects the optical and infrared images. The conclusions were as follows:

- the infrared K-images of the 3CR are scarcely affected by the alignment effect (Best, Röttgering & Longair 1998).
- the excitation mechanism for the radio sources with physical scales less than 120 kpc is shock emission, while in the larger radio sources, the excitation is due to photoionisation (Best, Röttgering & Longair 2000).
- the shock excitation of the smaller aligned sources can be attributed to the passage of the strong shock associated with the supersonic expansion of the lobes of the radio source components.

3. THE 6C SAMPLE

The next task was to extend these studies to fainter radio samples with a view to separating out effects associated with radio luminosity and those with cosmological epoch. This was achieved by studying a matched redshift sample of radio galaxies with flux densities a factor of 6 fainter than the 3CR sample. Another reason for studying this sample was that these radio galaxies were about 0.8 magnitudes fainter in absolute magnitude than the 3CR sample.

We repeated the analysis for the new 6C sample and arrived at the following conclusions (Inskip *et al.* 2002b).

- The alignment effect was similar to what had been found before, but the effects were not as pronounced as in the 3CR sample.
- A joint analysis of the two samples showed that the line widths of the radio galaxies in which we had identified the aligned emission as shock excitation of ambient clouds were very much broader than those which were photoionised. These shocks might well stimulate star formation in these structures.
- We were able to break the degeneracy between radio luminosity and redshift, showing that the changes in properties of the aligned structures are a redshift effect and not dependent upon the luminosity of the radio sources. Thus, there must be strong evolution of the host galaxies and/or their environments with redshift to account for the alignment effect.

4. THE MOST LUMINOUS RADIO GALAXIES

It was immediately apparent from our infrared images of the 3CR and 6C radio galaxies with redshifts $z \geq 1$ that the 3CR radio galaxies really are 'monster' galaxies – they are significantly more luminous in the K waveband than the 6C galaxies. We repeated our analysis of the K$-z$ relation for the 3CR and 6C samples for the concordance cosmological model ($\Omega_0 = 0.3, \Omega_\Lambda = 0.7$) and found that, because the time-scale of that world model is increased relative to that with $\Omega_\Lambda = 0$, the most distant radio galaxies had greater optical luminosities than they have at the present epoch, even when account is taken of the passive evolution of their stellar populations (Inskip *et al.* 2002a). The stellar masses of the radio galaxies in the redshift interval $0.5 \leq z \leq 2$ are almost $10^{12}\,M_\odot$, greater than those of the galaxies found in the Gemini Deep Deep Survey as well as the K20 survey over the same redshift interval.

If indeed the 3CR radio galaxies increase in mass with increasing redshift, this runs counter to the preferred hierarchical scenario for the formation of these galaxies which should increase, rather than decrease, in mass with cosmic epoch. However, the story is likely to be more complicated than this. Most recently, we have analysed the optical-infrared colours of the 3CR and 6C galaxies, attempting to remove the effects of the strong emission lines and any nuclear emission from the galaxies (Inskip *et al.* 2006). When this is done, the galaxies do not lie on the expected colour-redshift relation of a passive evolving giant elliptical galaxy. Rather the galaxies are 'bluer' than would be expected in these models. Perhaps surprisingly, both the 3CR and 6C samples show the same form of colour-redshift relation, despite the fact that the 6C galaxies are intrinsically fainter and the alignment effect less pronounced.

These results complicate the interpretation of these data. The mostly likely explanation is that there is indeed ongoing star formation in these galaxies, despite the fact that their light distributions are very well fitted by the de Vaucouleurs profiles of 'old, dead' giant elliptical galaxies. Evidence of continuing star formation in radio galaxies when their colours are taken into account was already found in

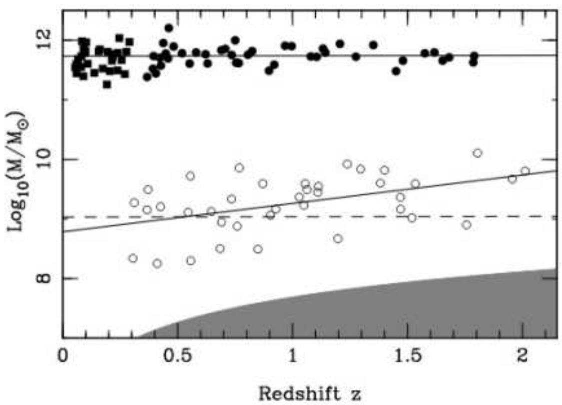

Fig. 4. Comparison of the masses of the black holes in 3CR radio quasars and the stellar masses of the bulges of the 3CR radio galaxies (McLure *et al.* 2006).

the earlier analysis of Dunlop *et al.* (1990). In addition, in their recent analysis of radio-loud galaxies in the SDSS Galaxy survey, Best *et al.* (2005) found that the probability of massive galaxies being FRII radio sources was remarkably high and a very strong function of the stellar mass of the galaxy. Since the lifetimes of the radio source events are at most $10^7 - 10^8$ years, there must therefore be continuing radio source events throughout the lifetimes of the most massive galaxies to account for such high probabilities. If the fuelling of the active nucleus which gave rise to the FRII radio source phenomenon were associated, for example, with a merger, there is very likely to be an associated burst of star formation. It does not require large amounts of star formation to account for the observed 'blueness' of the radio galaxies. The upshot is that a purely passively evolving stellar population is probably an oversimplification for these massive radio galaxies.

5. THE BULGE-BLACK HOLE CORRELATION FOR 3CR RADIO GALAXIES AND QUASARS

McLure *et al.* (2005) have used the unification picture for the 3CR radio galaxies and quasars discussed in Section 1 to investigate the bulge-black hole correlation for the most massive galaxies and active nuclei. Since we have argued that the 3CR radio galaxies and radio quasars are members of the same population observed at different angles to the line of sight, stellar masses can be determined using population synthesis models while the masses of the black holes can be estimated from the widths of the broad-line emission lines in the quasars. The results of this analysis is shown in Fig. 4.

The intriguing result shown in Fig.4 is that the black hole-bulge ratio is about 0.002 at redshifts $z < 1$, exactly the same value found for quite independent samples of active galactic nuclei. Now, however, the relation refers to samples of the most massive galaxies and black holes known. McLure and his colleagues argue that the ratio increases to about 0.008 by a redshift of 2, as suggested by the trends seen in Fig. 4. The important conclusion is that the black hole-bulge relation seems to hold even for the most massive galaxies we know of and that this was already in place by a redshift of 2.

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